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Assessing the environmental sustainability of irrigation with oil and gas produced water in drylands

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ABSTRACT

Produced water (PW) is the largest by-product of the oil and gas industry. Its management is both economically and environmentally costly. PW reuse for irrigation offers an alternative to current disposal practices while providing water to irrigators in drylands. The aim of this investigation was to evaluate the environmental effects of irrigation with PW. The SALTIRSOIL_M model was used to simulate the irrigation of sugar beet with 15 PWs of a wide range of qualities in four climates of different aridity and on four contrasting soil types. The impacts on soil salinity, sodicity and pH as well as on crop yield and drainage water salinity were estimated. Well-drained soils with low water content at field capacity (Arenosol) are less sensitive to salinisation while a relatively high gypsum content (Gypsisol) makes the soil less vulnerable to both sodification and salinisation. On the contrary, clayey soils with higher water content at field capacity and lower gypsum content must be avoided as the soil structural stability as well as a tolerable soil electrical conductivity for the crop cannot be maintained on the long-term. Soil pH was not found to be sensitive to PW quality. Drainage water quality was found to be closely linked to PW quality although it is also influenced by the soil type. The impact of drainage water on the aquifer must be considered and reuse or disposal implemented accordingly for achieving sustainable irrigation. Finally, increasing aridity intensifies soil and drainage water salinity and sodicity. This investigation highlights the importance of adapting the existing irrigation water quality guidelines through the use of models to include relevant parameters related to soil type and aridity. Indeed, it will support the petroleum industry and irrigators, to estimate the risks due to watering crops with PW and will encourage its sustainable reuse in water-scarce areas.

1. Introduction

Oil and gas (O&G) extraction generates considerable volumes of ‘produced water’ (PW) which is the main by-product of the O&G industry (Veil, 2011). PW mostly originates from water which is naturally present with the hydrocarbons in the reservoir, but can also include water that is artificially added to the reservoir and flows back to the surface during enhanced oil recovery and hydraulic fracturing (Engle et al., 2014). About half of the global PW volume is injected into disposal wells or discharged on the surface after treatment without being beneficially reused (Echchelh et al., 2018). These disposal practices have limits. Deep injection is energy intensive, and thus is expensive and is responsible for high CO_2 emissions (Arthur et al., 2011). Furthermore, it is environmentally hazardous, as it can pollute the groundwater (Hagström et al., 2016) and induce seismic activity (Walsh and Zoback, 2015). Surface discharge can also contaminate soils (Konkel, 2016) and receiving water bodies (Christie, 2012). As a consequence, stricter environmental regulations are being developed requiring extensive PW treatment before discharging (Fakhru’l-Razi et al., 2009) or prohibiting discharge entirely, e.g. Zero Liquid Discharge (Igunnu and Chen, 2014). The increasingly stringent regulation increases PW management cost for O&G firms (Stanic, 2014). As global PW volume is expected to rise drastically (Dal Ferro and Smith, 2007), there is a need for sustainable alternatives to current PW management practices.

PW reuse for irrigation could potentially provide a considerable amount of water to farmlands situated in O&G basins (Echchelh et al., 2018). This option is of the utmost interest in drylands which host a significant part of the world’s hydrocarbon production and reserves (EIA, 2018), and where water scarcity is likely to be exacerbated as a result of climate change (Feng and Fu, 2013) and population growth (Safriel et al., 2006). Therefore, to respond to both water scarcity and

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the environmental-economic limits of traditional PW disposal practices, the reclamation of PW for irrigation in dry areas must be considered.

Despite the large volume available, PW salinity, sodicity and metalloids contents often exceed the maximum levels recommended in the FAO irrigation water quality guidelines (Alley et al., 2011), thus preventing its application to the soil without adequate treatment. In Oman, for instance, following irrigation with partially treated PW; the electrical conductivity (EC_e) and the soil sodium adsorption ratio (SAR_e) of the soil saturation extract dramatically increased from 1.6 to 7.1 dS/m for the EC_e and from 2.3 to 68.1 for the SAR_e after 102 days of irrigation. As a result, the soil saturated hydraulic conductivity decreased from 1.42×10^{-3} to 1.6×10^{-6} m/s (Hirayama et al., 2002). Similarly, in semi-arid USA, when untreated PW was used to irrigate camelina, the soil EC_e increased from 1.4 to 1.9 dS/m while the soil SAR_e rose from 0.2 to 2.0 (Sintim et al., 2017). Comparable observations have been reported in other semi-arid regions of the USA (Burkhardt et al., 2015; Johnston et al., 2008), North-East Brazil (Sousa et al., 2017), South Africa (Beletse et al., 2008) as well as in dry sub-humid Australia (Biggs et al., 2013). Although these changes to soil properties may not immediately affect crop productivity, the long-term implications of irrigation using PW without soil salinity and sodicity management are uncertain.

Most research addressing the impacts of irrigation with PW is composed of short-term field experiments (1–3 years) whereas, O&G fields longevity varies from 5 to more than 50 years (Encana, 2011; Total, 2015). Moreover, field trials are carried out under specific climates and on particular soils, so their results cannot be easily extrapolated to other types of drylands. Also, the qualities of the PWs used in these trials do not necessarily represent the diversity of PW qualities. Therefore, there is a need for extending the study of the impacts on soil fertility in the long-term of irrigation with PW of different qualities on soil fertility in the long-term and under different climates and soil types.

To this end, simulation with soil-water models such as SALTIRSOIL_M (Visconti et al., 2014) is an adequate methodology for studying the long-term impacts of irrigation with a range of representative PWs on multiple soils and climates typical of drylands. Modelling is an appropriate tool, firstly because it reduces the time needed for obtaining results compared to field experiments. Also, models can be run with 'what-if' scenarios describing different situations without the need for a large number of field trials. Lastly, models allow the simulation of extreme scenarios without any adverse consequences on the environment (Graves et al., 2002). Although Mallants et al. (2017) and Jakubowski et al. (2014) modelled the impacts of irrigation with PW on soil salinity on the medium-term (1–10 years), they did not consider the long-term sustainability of this practice. In addition, these studies were limited to dry sub-humid Queensland, Australia.

This investigation aims to estimate the environmental sustainability of irrigation with PW in dry conditions and to determine how it is affected by environmental parameters (PW quality, climate and soil type). Here, sustainable irrigation refers to maintaining soil fertility in the long-term (i.e. indefinitely), which means to preserve soil structural stability and maintain a crop yield of at least 50% of optimum potential. For that, salinity (EC_e), sodicity (SAR_e) and pH (pH_e) of the soil saturation extract must be preserved from the effects of the irrigation water salinity (EC_w), sodicity (SAR_w) and pH (pH_w). Sustainable irrigation also includes appropriate management of drainage water (DW) depending on its salinity (EC_d) and sodicity (SAR_d). The impacts of irrigation with PW on soil fertility, DW quality and crop yield are discussed from an environmental perspective.

2. Materials and methods

2.1. Soil-water model

SALTIRSOIL_M is a one-dimensional, deterministic, transient-state model with a monthly time step (Visconti, 2013). Based on a tipping-bucket algorithm, it simulates the water movement through a number of soil layers (n) and down to a specific soil depth chosen by the user. As a result, the model calculates a concentration factor of the soil solution regarding the irrigation water ($f_{i,j} = C_{SSi,j}/C_{Ii}$), for each month i and soil layer j with Eqs. (1) and (2), where $C_{SSi,j}$ is the concentration of the kth ion in the soil solution of the jth layer in the ith month, and C_{Ii} is the concentration of the kth ion in the irrigation water in the ith month. Eq. (1) expresses the soil solution concentration factor for the first soil layer ($j = 1$), and Eq. (2) for subsequent layers.

$$\boldsymbol{f}_{i,1} = \frac{\boldsymbol{V}_{i-1,1}\boldsymbol{f}_{i-1,1}\left(\frac{C_{Ii-1}}{C_{Ii}}\right) + \boldsymbol{I}_i}{\boldsymbol{V}_{i,1} + \boldsymbol{D}_{i,1}} \tag{1}$$

$$\boldsymbol{f}_{i,j} = \frac{\boldsymbol{V}_{i-1,j}\boldsymbol{f}_{i-1,j}\left(\frac{C_{Ii-1}}{C_{Ii}}\right) + \boldsymbol{D}_{i,j-1}\boldsymbol{f}_{i,j-1}}{\boldsymbol{V}_{i,j} + \boldsymbol{D}_{i,j}} \tag{2}$$

In Eqs. (1) and (2), $f_{i,j-1}$ is the concentration factor in the previous month, $V_{i,j}$ and $V_{i-1,j}$ are, respectively, the soil water content of the soil layer j in the month i and in the previous ($i - 1$) month, $D_{i,j}$ and $D_{i,j-1}$ are, respectively, the drainage amount from the soil layer j and from the overlaying ($j - 1$) layer in the month i, C_{Ii-1}/C_{Ii} is the quotient of the irrigation water concentration the previous ($i - 1$) regarding the present (i) month, and finally, I_i is the irrigation water amount in the present month (i).

The main ion concentrations in the irrigation water ([k] where k = Na^+, K^+, Mg^{2+}, Ca^{2+}, Cl^-, $SO_4{}^{2-}$ and $NO_3{}^-$) are multiplied by the monthly averages of the soil solution concentration factors from the 1st down to the nth layer chosen by the user ($\bar{f}_i$), and besides, by the quotient of the soil water content at saturation (θ_e) to the soil water content at field capacity (θ_{fc}) (Eq. (3)).

$$[k]_{e,i} = \frac{\theta_e}{\theta_{fc}}\bar{f}_i\,[k]_i \tag{3}$$

As a result, the main ion composition of monthly soil saturation extracts away from chemical equilibrium is obtained. These ion concentrations are then entered into a chemical equilibrium model that calculates the soil solution ionic composition at equilibrium by letting calcite ($CaCO_3$) and gypsum ($CaSO_4{\cdot}2H_2O$) precipitate or dissolve, if present, at the specified CO_2 partial pressure (pCO_2). Finally, the soil pH_e and the EC_e at 25 °C are calculated, the latter by using, in addition to ion concentrations, their ionic conductivities.

The month-by-month year-round ionic composition, pH_e and EC_e calculated with the model represents the steady state that would be reached in the long-term under constant irrigation water composition, irrigation management, climate features, soil physical properties and crop.

The SALTIRSOIL_M model has been successfully used to predict the equilibrium soil ionic composition and EC_e of irrigated semi-arid lands in Spain (Visconti et al., 2014). In this research, the model is used to calculate the equilibrium EC_e, SAR_e, and pH_e of the soil saturation extract and of the DW.

2.2. Model parameterisation

Locations from the western USA, preferably near O&G fields, were chosen to represent the different types of dry climates (Table 1). Dry climates are classified using the UNEP aridity index (AI) which is defined as the ratio of precipitation and potential evapotranspiration (Cherlet et al., 2018). A climate is hyper-arid if AI < 0.05, arid if 0.05 ≤ AI < 0.20, semi-arid if 0.20 ≤ AI < 0.50 and dry sub-humid if 0.5 ≤ AI < 0.65. Monthly climatic averages were calculated from daily time series for the period 1990–2016. Temperature, relative humidity, precipitation, reference evapotranspiration (ETo), wind speed and downward solar radiation, were sourced from the University of Idaho's METDATA (Abatzoglou, 2013) and the average number of days with

Table 1
Parameters of climate, crop development and irrigation schedules used in the simulations.

	Parameter	January	February	March	April	May	June	July	August	September	October	November	December	Total
Hyper-arid: Yuma, Arizona	P (mm)	10	10	7	3	1	0	6	8	11	6	6	10	78
(AI = 0.04)	ETo (mm)	80	93	144	184	232	254	269	249	194	138	90	72	2000
	I (mm)	105	133	218	285	349	306	115	0	0	0	43	59	1612
Arid: Bakersfield, California	P (mm)	31	31	27	13	6	1	0	0	2	9	12	26	157
(AI = 0.09)	ETo (mm)	47	64	112	157	220	254	265	238	180	125	66	45	1773
	I (mm)	33	65	147	244	346	329	123	0	0	0	20	13	1320
Semi-arid: Santa Fe, New Mexic	P (mm)	16	14	18	18	25	27	62	55	40	35	22	25	357
(AI = 0.23)	ETo (mm)	50	64	106	144	190	215	180	159	137	108	67	47	1468
	I (mm)	58	85	147	202	252	224	53	0	0	0	14	19	1054
Dry sub-humid: Dallas, Texas	P (mm)	70	66	92	94	123	102	50	62	68	113	74	79	991
(AI = 0.64)	ETo (mm)	64	74	113	146	174	201	226	203	153	117	77	62	1609
	I (mm)	13	36	74	123	142	139	63	0	0	0	0	0	590
Crop growth	K_{cb}	0.70	1.15	1.20	1.20	0.93	0.70	0.41	0	0.	0	0.41	0.70	–
	Root depth (cm)	49	56	84	92	100	100	100	0	0	0	15	30	–

AI: Aridity index, P: precipitation; ETo: reference evapotranspiration; I: irrigation; K_{cb}: basal crop coefficient.

precipitation from Weatherbase (Canty et al., 2018). The number of sunshine hours was estimated using the adapted equation of Ångström-Prescott (Viswanadham and Ramanadham, 1969).

The Harmonised World Soil Database (FAO, 2009) was used to select four representative soil types according to FAO's Reference Soil Groups (RSG) classification (IUSS Working Group WRB, 2015). The selected soil types –Gypsisol, Arenosol, Planosol and Vertisol– represent ˜22%, ˜12%, ˜5% and ˜5% respectively of soils in drylands (Koohafkan and Stewart, 2008). All soil samples belonging to the same soil type were grouped and their parameters values averaged to create an indicative soil for each soil type. The soil volumetric water contents at saturation and field capacity were estimated from the soil texture and organic matter content (Saxton and Rawls, 2006). The soil organic matter content (SOM) was estimated from the total organic carbon content using a Van Bemmelen factor of 1.72 (Soil Survey Staff, 1996). The pCO_2 was estimated from soil pH (Thomas, 1996) (Table 2).

Tropical sugar beet was selected as an exemplar crop for the following reasons. Firstly, it is salt-tolerant (Tanji and Kielen, 2002), sodium and chloride-tolerant (Wakeel et al., 2010) and it can be grown in a wide range of soils (SESVanderHave, 2016) and under dry climates (Chatin et al., 2004; Nilsson, 2005). Secondly, sugar beet usually adapts well to drip irrigation, which is the most suitable system in water-scarce drylands (Rhoades et al., 1992). Finally, this crop has multiple uses such as foodstuff (sugar), animal feed (pellets and molasses) and biofuel. The planting date was set on November 1st, a typical planting date in the Northern hemisphere regions with Mediterranean arid climates (FAO, 2018a). Crop coefficients, growth stages lengths and root depths were obtained from FAO (2018a[FAO,2018b]). The shaded area values were sourced from Webb et al. (1997).

CROPWAT 8.0 (FAO, 2018b) was used to estimate the crop water requirements and to set the irrigation schedule for each climate (Table 1). No deliberate leaching nor amendments were included.

2.3. Produced water quality

Data on PW origin and quality for 33 PWs were sourced from the USGS National Produced Waters Geochemical Database (Blondes et al., 2017). An exploratory data analysis of the ten physicochemical water properties (EC_{25}, pH, $[Na^+]$, $[K^+]$, $[Mg^{2+}]$, $[Ca^{2+}]$, $[Cl^-]$, $[NO_3^-]$, $[SO_4^{2-}]$ and alkalinity (Alk)) was carried out in the 33 PWs. The distributions of these properties fulfilled the requirements for log-normally distributed variables with the exception of pH, being this last one normally distributed. However, inspection of the histograms revealed some data clustering that could diminish the precision of the sustainability assessment. Since having more regularly distributed data would be optimal, a stochastic PW generator (SPWG) was developed on the basis of the 33 PW according to the methodology outlined in the ensuing paragraph.

First of all, the original water properties were log-transformed with the exception of pH, and their means and standard deviations assessed. Second, a principal components analysis (PCA) was performed on the log-transformed data table of 33 PWs and, as a consequence, its matrix of eigenvectors was obtained. Third, independent random values were obtained from a marginal normal distribution with zero mean and one standard deviation for each of the 10 principal components (PCs) of a set of 1000 synthetic waters. Four, the logarithmic values of the 10 physicochemical water properties in all these synthetic waters were calculated using the previously obtained matrix of eigenvectors in addition to the corresponding means and standard deviations, which we know from the first step. Five, these logarithmic values for the ten properties in the set of 1000 synthetic waters were back-transformed to become normal. Six, the charge balance errors (CBE) were calculated in

Table 2
Parameters of the four soils used in the simulations.

Soil type	Soil layer (cm)	Hydrophysical			USDA texture (%)			Chemical				
(FAO's RSG)		ρ_b (g/cm^3)	θ_{fc} (%)	θ_{pwp} (%)	Sand	Silt	Clay	pH	Gypsum (%)	CCE (%)	SOM (%)	log pCO_2
Arenosol	Topsoil 0–30	1.70	10	5	89	6	5	6.1	0.02	0.74	0.58	0
	Subsoil 30–100	1.69	10	5	89	5	6	6.1	0.02	0.81	0.27	0
Gypsisol	Topsoil 0–30	1.42	28	14	45	34	21	7.9	12.57	6.42	0.57	−3
	Subsoil 30–100	1.38	31	11	41	33	26	7.9	16.99	5.62	0.30	−3
Planosol	Topsoil 0–30	1.43	36	25	51	29	20	5.7	0.01	0.16	1.45	0
	Subsoil 30–100	1.33	36	22	40	25	35	6.3	0.01	0.58	0.59	0
Vertisol	Topsoil 0–30	1.22	42	30	22	24	54	7.2	0.14	2.39	1.81	−2
	Subsoil 30–100	1.21	42	30	21	23	57	7.6	0.19	3.64	0.99	−2

FAO RSG: FAO Reference Soil Groups, ρ_b: bulk density; θ_{fc}: maximum soil volumetric water content at field capacity; θ_{pwp}: maximum soil volumetric water content at permanent wilting point; CCE: calcium carbonate equivalent.

Table 3
Quality of the different PWs used for irrigation simulations ranked by increasing EC_w (all ions contents are expressed in mmol/L, alkalinity in $mmol_c$/L and EC_w in dS/m).

	$[Na^+]$	$[K^+]$	$[Ca^{2+}]$	$[Mg^{2+}]$	$[Cl^-]$	$[NO_3^-]$	$[SO_4^{2-}]$	Alk_w	EC_w	SAR_w	pH_w
PW1	1.1	0.0	0.0	0.0	0.1	0.0	0.0	0.9	0.3	10	7.1
PW2	9.1	0.1	0.4	0.1	3.3	0.0	0.1	6.8	0.9	13	6.8
PW3	7.4	0.1	4.9	0.2	8.8	0.0	0.1	8.1	1.6	3	6.0
PW4	36.0	0.3	4.2	2.7	47.6	0.0	0.2	2.7	4.5	14	5.6
PW5	46.4	0.7	11.5	0.7	65.7	0.1	0.2	3.9	6.3	13	7.5
PW6	58.6	0.2	26.4	0.9	102.2	0.0	0.2	10.6	9.9	11	6.2
PW7	51.8	0.1	38.9	2.9	127.9	0.1	0.3	6.7	12.1	8	5.6
PW8	124.4	6.7	8.7	9.3	166.2	0.0	0.7	2.0	14.4	29	6.7
PW9	190.8	1.9	2.7	2.6	195.8	0.0	0.5	1.3	16.7	83	6.5
PW10	179.5	1.4	23.2	2.1	198.2	0.0	0.4	28.1	18.9	36	6.7
PW11	103.7	0.5	101.9	7.4	307.3	0.0	0.9	1.9	27.9	10	6.6
PW12	466.4	0.2	2.0	5.2	488.0	0.0	0.4	3.8	38.5	174	7.6
PW13	559.4	6.4	17.2	6.4	589.3	0.0	0.9	2.1	47.3	115	6.8
PW14	759.1	2.1	36.7	31.6	918.4	0.0	1.7	2.6	71.3	92	6.8
PW15	866.4	1.2	220.5	126.8	1572.2	0.0	3.9	3.9	130.3	47	7.2

every synthetic water and the waters exceeding ± 2% were deleted from the dataset. Finally, just 15 waters regularly covering a wide range from 0.3 to 130.3 dS/m were kept and used in the simulations (Table 3).

2.4. Model scenarios

The 240 simulated scenarios represent the irrigation with each PW (15) on each soil type (4) and under each climate (4). The soil depth chosen for the simulation was 60 cm because this is the depth where sugar beet root density is the highest (Draycott, 2006). All results of soil composition were expressed for a saturated extract at chemical equilibrium.

2.5. Sustainability assessment

Soil fertility was appraised using the calculated indicators SAR_e and EC_e, which were compared to threshold values. Threshold SAR_e values for soil structural stability were based on the Australian and New Zealand Environment Conservation Council guidelines (ANZECC, 2000) which have been used as a reference to study the risks and feasibility of irrigating with PW under dry climates in Australia and in sub-Saharan Africa (Horner et al., 2011; Mallants et al., 2017). The thresholds for SAR_e were set at 20 for Arenosol (sandy soil with clay content < 15%), 20 for Gypsisol (loamy soil with 15% < clay content < 24%), 13 for Planosol (clay loam soil with 25% < clay content < 34%) and 5 for Vertisol (clayey soil with 55% < clay content < 64%). Due to the critical importance of SAR_e for soil stability, no scenario could be considered sustainable if the simulated soil SAR_e exceeded the ANZECC guidelines thresholds.

Soil EC_e was evaluated through the expected effects on sugar beet yield considering the FAO salt tolerance parameters given by Shaw et al. (2011). That is, an EC_e of 7 dS/m for a maximum yield and a productivity decrease of 5.9% per dS/m increase of EC_e. Therefore, taking a minimum yield of 50% of its potential, the resulting maximum EC_e is 15.5 dS/m.

The quality of DW can affect the sub-soil and the aquifer. In fact, DW can carry dissolved salts into the aquifer and depending on its depth, it may result in groundwater salinisation (Shannon et al., 1997). DWs qualities are ranked according to their EC_d (Rhoades et al., 1992) to consider their impacts on groundwater and the implications.

In addition, soil pH_e was used as a complementary indicator for assessing the risk of nutrient deficiencies which have an impact on crop yield and quality (McEnroe and Coulter, 1964). The pH_e threshold values are the suitable range of values for sugar beet cultivation (SESVanderHave, 2016).

2.6. Statistical analyses

Three-way analyses of variance (ANOVA) were used to check for significant differences among soils, climates and PWs in the determination of the soil chemistry (i.e. EC_e, SAR_e and pH_e) and DW quality (i.e. EC_d and SAR_d) characteristics. Besides, two-way ANOVAs were also performed to check for significant first order interactions (second order effects) between soils, climates and PWs in the determination of the same characteristics.

Linear regressions were used to study the strength of the (linear) dependence (R^2) and strength of the effect (line slope) of the PW characteristics on their soil counterparts, i.e., EC_w on EC_e, SAR_w on SAR_e and, especially Alk_w on pH_e, under the influence of the different soil types (Fig. 3) and climates considered in this work (Fig. 4).

3. Results

The impact of irrigation with PW on the long-term soil salinity and sodicity of the 240 scenarios are presented in Fig. 1. The DWs resulting from irrigation are classified by their level of salinity in Fig. 2. The salinity and sodicity balances between the different salt reservoirs –irrigation water, soil and DW– are described by the slope of the curves in Figs. 3 and 4.

According to the three-way ANOVA PW but also, soil and climate, significantly influence the soil chemistry and DW quality. The ranking of the mean square values in descending order indicate that the EC_e and SAR_e were mainly determined by PW, then soil, and finally climate. Climate was not determinant for the pH_e as the latter was mainly determined by soil and PW. Lastly, the EC_d was shown to be mostly influenced by PW and to a lesser extent by climate whereas the SAR_d was influenced by PW, climate and finally soil (Table 4). According to the two-way ANOVAs the interaction between PW and soil was significant on the determination of EC_e, SAR_e and pH_e, but not the others (i.e. soil x climate and climate x PW). However, the interaction between climate and PW has a significant effect on DW quality (EC_d and SAR_d).

Soil salinity and sodicity showed a remarkable linear dependence on PW salinity and sodicity according to the high R^2 in Figs. 3 and 4. The curves $EC_e = f(EC_w)$ in Fig. 3 indicate how prone the different soils are to salinisation because of salt transfer from the irrigation water to the soil. The slope of the curve $EC_e = f(EC_w)$ was the steepest for Vertisol (1.01), Planosol (0.87), Gypsisol (0.65) and finally Arenosol (0.23). On the other hand, the curves $EC_d = f(EC_w)$ illustrate how dependent on PW is DW salinity in each soil type. In this case, the slope of this curve was the highest for Arenosol (2.10), Vertisol (1.85), Planosol (1.84) and finally Gypsisol (1.82). Likewise, the curves $SAR_e = f(SAR_w)$ indicates the soil sensitivity to sodification due to the transfer of sodium from the

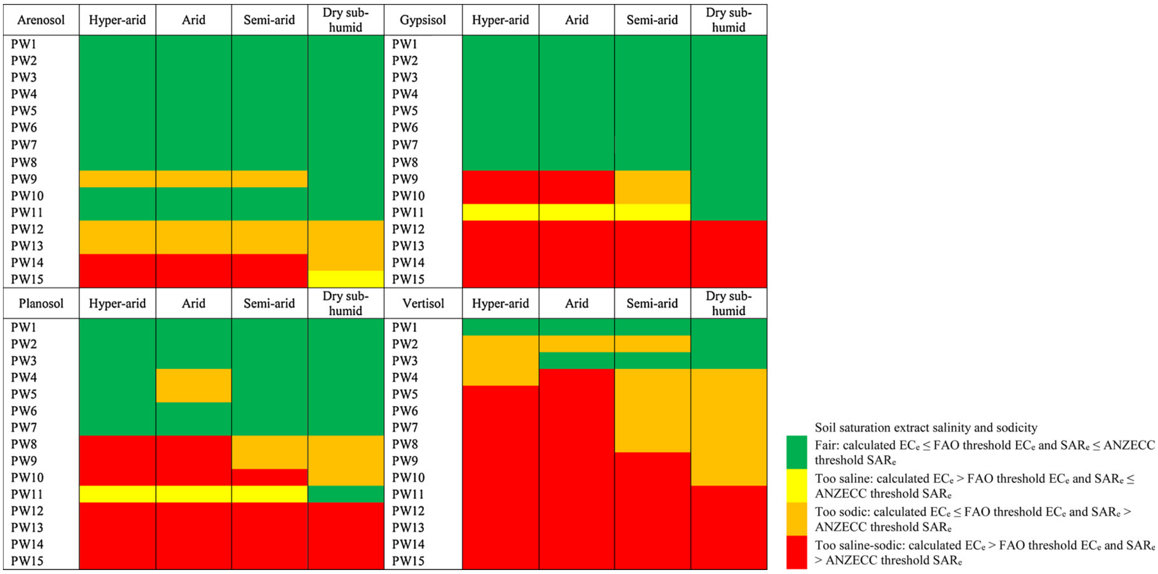


Fig. 1. Salinity and sodicity of the soil solution in the long-term as a result of irrigation with 15 PWs under hyper-arid, arid, semi-arid and dry sub-humid climates and on Arenosol, Gypsisol, Planosol and Vertisol. The SAR_e threshold values are 20 for Arenosol and Gypsisol, 13 for Planosol and 5 for Vertisol. The limit EC_e value for sugar beet cultivation is 15.5 dS/m, below this value crop yield is lower than 50% of its optimum.

irrigation water to the soil. The slope of this curve was the steepest for Vertisol (0.94), Planosol (0.88), Arenosol (0.54) and Gypsisol (0.42). Next, the curves $SAR_d = f(SAR_w)$ indicate the ability of the soil to buffer the calcium and magnesium concentrations of the water that percolates through it. In this case, the slope of this curve was the highest for Planosol (1.32), Vertisol (1.32), Arenosol (1.05) and Gypsisol (0.90).

The impact of irrigation with PW on soil salinity and sodicity is also influenced by climate and, specifically, it can be amplified by the increasing aridity (Fig. 4). Indeed, all soils combined, the slopes of the curves $EC_e = f(EC_w)$ and $SAR_e = f(SAR_w)$ from highest to lowest were as follow: Hyper-arid (0.89 and 0.96), arid (0.89 and 0.75), semi-arid (0.68 and 0.66) and dry sub-humid (0.40 and 0.45) respectively. Whereas the slopes of the curves $EC_d = f(EC_w)$ and $SAR_d = f(SAR_w)$ from highest to lowest were as follow: Arid (2.56 and 1.35), hyper-arid (2.25 and 1.33), semi-arid (1.70 and 1.01) and dry sub-humid (1.08 and 0.81) respectively.

According to R^2, soil pH_e was not dependent on PW quality in Gypsisol and Vertisol, whereas it was somewhat more dependent in the case of Arenosol and Vertisol (Fig. 6). There was no risk of crop yield loss due to unsuitable pH_e as tropical sugar beet can be grown in soil with pH ranging from 4 to 9. Instead, crop yield responded negatively to increasing EC_e.

4. Discussion

4.1. Soil salinity and sodicity

The three-way ANOVA revealed that, in the long-term, PW quality, soil type and climate influence (in this order from the most to the least influential) soil salinity and sodicity (Table 4). Besides, the two-way ANOVA revealed that the only significant interaction was between PW and soil. That is to say, the effect of PW on soil salinity, sodicity and pH was significantly modulated by the soil type (Table 4). In all scenarios, increasing EC_w and SAR_w led to a higher degree of soil salinisation and/

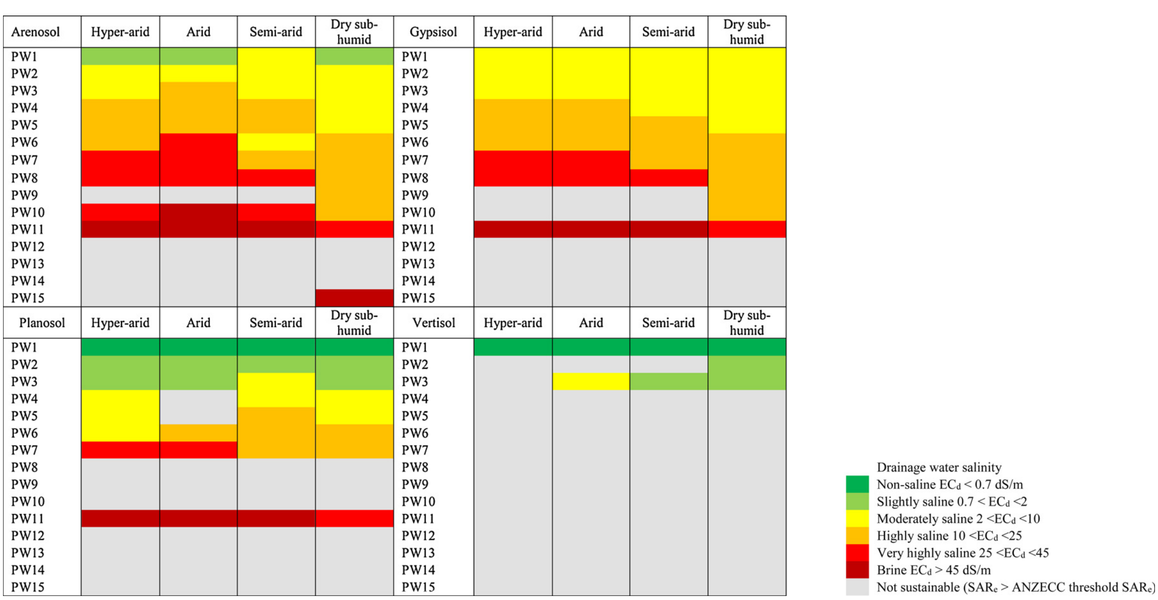
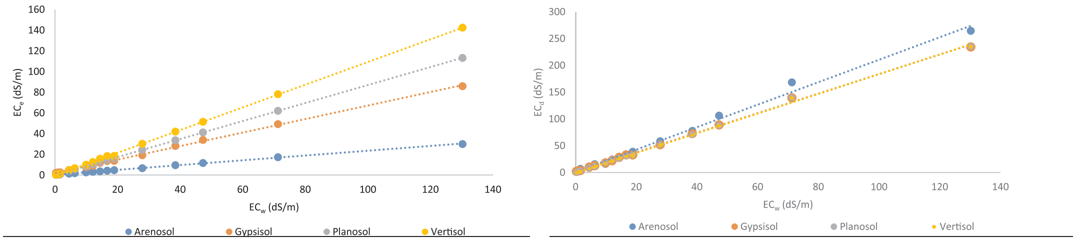
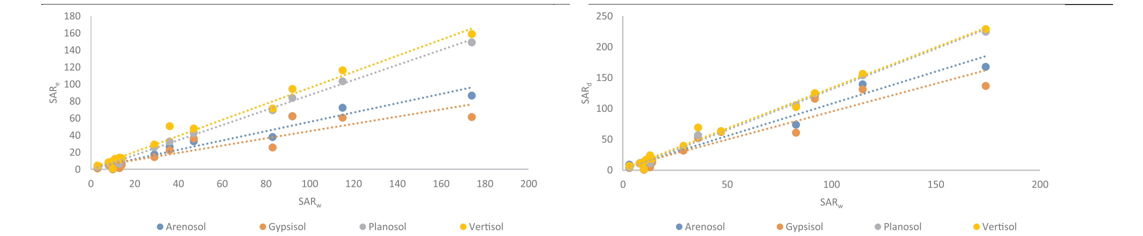


Fig. 2. Drainage water salinity leaving the root zone (0–60 cm) of the selected sustainable (fair soil salinity) and likely sustainable scenarios (too saline soils) in Fig. 1.



Soil	Arenosol	Gypsisol	Planosol	Vertisol
Curve equation	$EC_e = 0.231\ EC_w + 0.513$	$EC_e = 0.652\ EC_w + 2.058$	$EC_e = 0.869\ EC_w + 0.167$	$EC_e = 1.096\ EC_w - 0.239$
R^2	0.9993	0.9989	1	0.9998

Soil	Arenosol	Gypsisol	Planosol	Vertisol
Curve equation	$EC_d = 2.096\ EC_w + 1.117$	$EC_d = 1.823\ EC_w + 1.675$	$EC_d = 1.836\ EC_w + 0.394$	$EC_d = 1.834\ EC_w - 0.134$
R^2	0.9931	0.9982	0.9984	0.9982



Soil	Arenosol	Gypsisol	Planosol	Vertisol
Curve equation	$SAR_e = 0.547\ SAR_w + 1.138$	$SAR_e = 0.424\ SAR_w + 2.629$	$SAR_e = 0.881\ SAR_w - 0.740$	$SAR_e = 0.941\ SAR_w + 1.748$
R^2	0.9545	0.8398	0.9956	0.9829

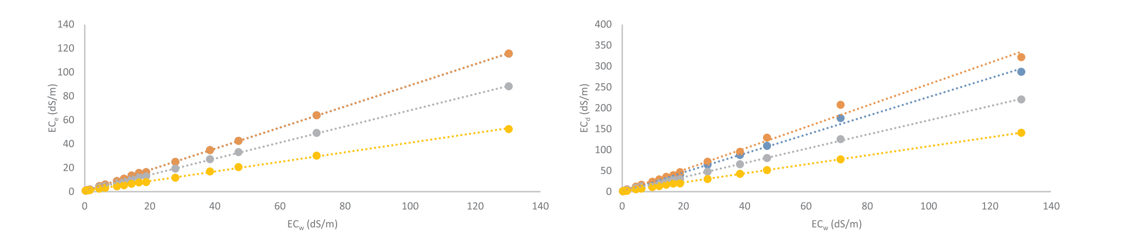
Soil	Arenosol	Gypsisol	Planosol	Vertisol
Curve equation	$SAR_d = 1.046\ SAR_w + 3.172$	$SAR_d = 0.907\ SAR_w + 4.519$	$SAR_d = 1.319\ SAR_w - 0.552$	$SAR_d = 1.316\ SAR_w + 2.080$
R^2	0.9543	0.9041	0.9951	0.9886

Fig. 3. Influence of soil type on the ratios EC_e/EC_w; EC_d/EC_w; EC_e/EC_d; SAR_e/SAR_w; SAR_d/SAR_w; SAR_e/SAR_d all climates combined.

or sodification (Fig. 1). This is illustrated by the values of the coefficients of determination (R^2) of EC_e against EC_w on the one hand, and SAR_e against SAR_w on the other hand. Therefore, independently of soil type (Fig. 3) and aridity (Fig. 4); irrigation using PWs with higher EC_w led to higher soil EC_e. Similarly, irrigation using PWs with higher SAR_w led to higher soil SAR_e. However, R^2 was lower for soil and water SAR than for soil and water EC, thus, soil sodicity (SAR_e) was less dependent on water sodicity (SAR_w) than soil salinity (EC_e) was on water salinity (EC_w) as other parameters related to the soil interfere and must be taken into account to predict SAR_e.

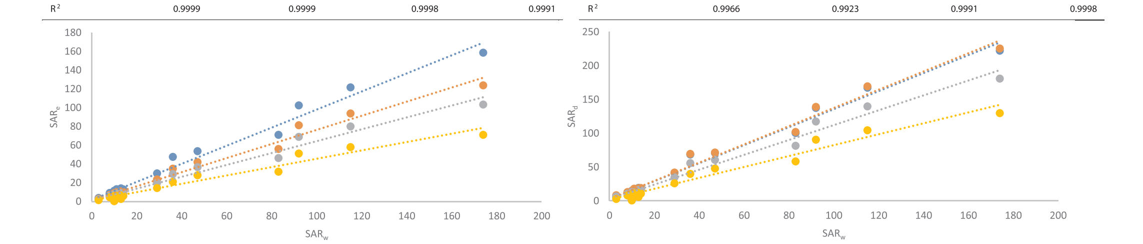
The simulations have shown that the soil types differed regarding their levels of vulnerability to sodification (Table 4 and Fig. 1). The clay content on which the ANZECC SAR_e threshold values are based (Shaw et al., 2011), has a key role in determining the sensitivity of a soil to sodification. Indeed, high SAR_e causes high exchangeable sodium percentage (ESP), which destabilise soil particles due to clay swelling and dispersion. As a result, soil pores clog and its hydraulic conductivity and thus, the ability to supply water to crops, decreases. Eventually, the sensitivity of lands to erosion and desertification are both amplified (Dregne, 1983; Qadir and Schubert, 2002).

The soil characteristics that mostly influence long-term SAR_e are gypsum content and drainage ability. Firstly, soil gypsum content buffers soil sodicity by dissolving into the soil solution. Secondly, the drainage properties of the soil moderate soil sodification because as the percentage of sand increases, water content at field capacity decreases and leaching increases and thus, the sodium concentration in the soil solution decreases, however, calcium concentration is more constant because this ion also dissolves into the soil solution from calcium



Climate	Hyper-arid	Arid	Semi-arid	Dry sub-humid
Curve equation	$EC_e = 0.886\ EC_w + 0.488$	$EC_e = 0.885\ EC_w + 0.489$	$EC_e = 0.675\ EC_w + 0.676$	$EC_e = 0.402\ EC_w + 0.847$
R^2	0.9999	0.9999	0.9998	0.9991

Climate	Hyper-arid	Arid	Semi-arid	Dry sub-humid
Curve equation	$EC_d = 2.253\ EC_w + 1.060$	$EC_d = 2.564\ EC_w + 0.808$	$EC_d = 1.700\ EC_w + 0.518$	$EC_d = 1.077\ EC_w + 0.667$
R^2	0.9966	0.9923	0.9991	0.9998



Climate	Hyper-arid	Arid	Semi-arid	Dry sub-humid
Curve equation	$SAR_e = 0.963\ SAR_w + 1.613$	$SAR_e = 0.753\ SAR_w + 1.124$	$SAR_e = 0.633\ SAR_w + 1.017$	$SAR_e = 0.445\ SAR_w + 1.020$
R^2	0.9768	0.9783	0.9738	0.9577

Climate	Hyper-arid	Arid	Semi-arid	Dry sub-humid
Curve equation	$SAR_d = 1.334\ SAR_w + 2.358$	$SAR_d = 1.348\ SAR_w + 2.687$	$SAR_d = 1.098\ SAR_w + 2.276$	$SAR_d = 0.806\ SAR_w + 1.898$
R^2	0.9812	0.9814	0.9762	0.9642

Fig. 4. Influence of aridity on the ratios EC_e/EC_w; EC_d/EC_w; EC_e/EC_d; SAR_e/SAR_w; SAR_d/SAR_w; SAR_e/SAR_d all soils combined.

Table 4
Summary of the results of the ANOVAs detailing the calculated mean square values, their significance (*** indicate that p value < 0.001, ** p value < 0.01, * p value < 0.05) and the degree of freedom (d.f.).

			Mean square values and significance				
Variation source	ANOVA	d.f.	EC_e	SAR_e	pH_e	EC_d	SAR_d
Soil	Three-way	3	8848***	13297***	74.41***	21	3346***
Climate	Three-way	3	4111***	3811***	0.04	31652***	13318***
PW	Three-way	14	16232***	23446***	0.24***	100291***	70900***
Residual	Three-way	219	328	320	0.02	654	340
Soil x Climate	Soil-Climate two-way	9	266	127	0.03	0	12
Residual	Soil-Climate two-way	224	1325	1773	0.04	6908	4763
Soil x PW	Soil-PW two-way	42	1068***	1274***	0.11***	1	623
Residual	Soil-PW two-way	180	219	156	0.00	1323	490
Climate x PW	Climate-PW two-way	42	490	332	0.0014	3409***	1130***
Residual	Climate- PW two-way	180	432	534	1.2673	1	205

minerals (calcite and mostly gypsum if present). As a result, the soils with the highest gypsum content, highest sand content and thus, lowest field capacity were the less prone to sodification. This was shown by the simulations, in which Vertisol and Planosol resulted to be the most sensitive to sodification whereas Gypsisol and Arenosol were the least vulnerable to sodification (Fig. 3). Field experiments have confirmed that the sensitivity of soil to sodification can be anticipated knowing the soil clay content and the water retention properties (Levy et al., 2005). The buffer effect of soil gypsum on SAR_e has also been highlighted in an experimental-modelling study with PW in semi-arid Wyoming, USA (Engle et al., 2011).

The long-term EC_e and therefore, the risk of soil salinisation also depends on soil type (Table 4 and Fig. 1). Indeed, soils with a low water content at field capacity, in general, drain more easily as they usually have large pores. Thus they retain less water and leach more salt compared to soils with a higher field capacity. As a consequence, Vertisol and Planosol were the most sensitive to salinisation whereas Gypsisol and Arenosol were the least vulnerable to salinisation (Fig. 3). An irrigation trial with PW conducted in semi-arid NE-Brazil on a sandy soil showed that the high porosity of Arenosols decreased EC_e through facilitated drainage (Sousa et al., 2017).

Although less than soil, climate also affects the relationships between water and soil salinity as well as between water and soil sodicity. Indeed, this was anticipated by the three-way ANOVA (Table 4), and then quantified by the slopes of the curves $EC_e = f(EC_w)$ and $SAR_e = f(SAR_w)$, which increased following aridity from dry sub-humid to hyper-arid (Fig. 4) making irrigation with PW less sustainable (Fig. 1). This is explained by the double effect of rain which both dilutes the soil solution and transport salts out of the root zone reducing EC_e. Equally important, higher evaporation increases the salt concentration of the soil-water. Lower aridity or higher humidity decreases the concentration of soil sodium while the concentrations of magnesium and, over all, calcium, are buffered by the minerals calcite and gypsum generally present in dryland soils (Koohafkan and Stewart, 2008). The ability of aridity to influence EC_e and SAR_e were observed in a field trial carried out with PW under humid sub-tropical climate in Alabama, USA (Mullins and Hajek, 1998). Thus, the aridity index should be considered when assessing the sustainability of irrigation with PW.

The crop has an indirect effect in determining EC_e and SAR_e. Sugar beet was considered in this study, however, other crops would have required different irrigation amounts and schedules. As the irrigation volume and its distribution play a key role for EC_e and SAR_e, a crop with lower water needs compared to sugar beet implies less irrigation water and thus less salt input to the soil. Also, if the crop requires water in the period of the year when rainfall is the highest and evaporation the lowest, it could highly reduce soil EC_e and SAR_e due to less irrigation, more salt leaching and less water evaporation.

In brief, well-drained soils with low clay content and significant gypsum content in the relatively most humid regions must be chosen in priority for preventing soil salinisation and sodification. In addition, a drought-resistant crop growing when the AI is the highest during the year must be privileged for improving the sustainability of irrigation with PW.

Most of the studies referring to the suitability of using PW for irrigation use the FAO guidelines (Ayers and Westcot, 1985) for assessing potential risks to the soil and crop (Beletse et al., 2008; Guerra et al., 2011; Martel-Valles et al., 2014, 2017, 2016; Myers, 2014). The results obtained in this investigation could help to refine these standards when assessing the sustainability of irrigation with PW. Indeed, the limitations of the FAO guidelines are that they are not specific, therefore they may be too conservative for environments with low vulnerability to salinisation and sodification (e.g. well-drained soils in dry sub-humid climates). Although the ANZECC guidelines are more specific by discriminating among soil types according to their clay content, they do not consider the degree of aridity in the determination of threshold EC_w and SAR_w values to prevent soil salinisation and sodification.

4.2. Soil pH

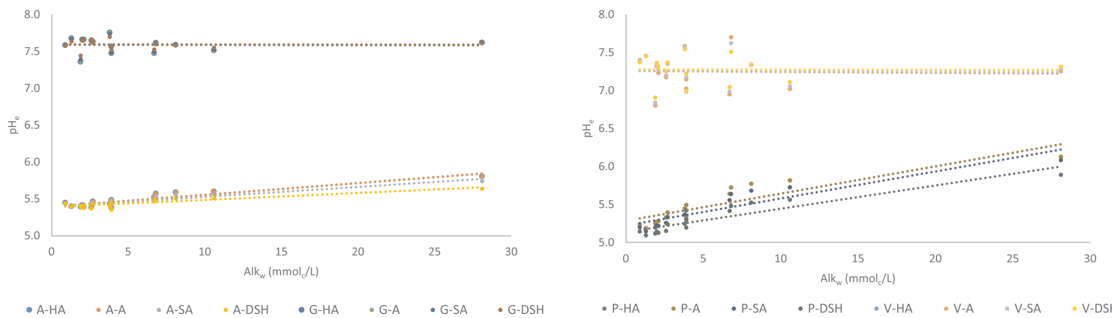
According to the three-way ANOVA soil pHe was mainly determined by the soil type (especially by the soil $CaCO_3$ content) and to a lesser extent by PW quality (Table 4). Only for Arenosol and Planosol –which have low carbonate content– the soil pH_e was positively influenced, although in a limited proportion, by irrigation water alkalinity (Alk_w) with $0.79 < R^2 < 0.86$, whereas the R^2 were very low (< 0.01) for Gypsisol and Vertisol, which both have the highest carbonate content (Fig. 5). The limited influence of irrigation water on pH_e has also been highlighted in an irrigation trial with PW on a Vertisol in dry sub-humid Australia (Bennett et al., 2016). Decreasing aridity slightly reduced pH_e on Arenosol and Planosol (Fig. 5), that is a common observation in arid environments (Jiao et al., 2016).

Soil amendments and fertilisers, which are not considered in this study may have a significant effect on pH_e which must be anticipated if they are used along with irrigation.

4.3. Crop yield

Crop yield can be maximised by reducing the soil EC_e below 7 dS/m which is the crop threshold value for an optimal yield (Fig. 6). The irrigation volume can be increased to leach more salt or PW can be blended with another water of lower salinity to reduce EC_e. Eventually, crop with a higher tolerance to salinity can be cultivated if it is adapted to climates and soils in drylands.

Although crop production is of primary relevance for farmers, the O&G industry does not necessarily have the same target. If managing PW in an irrigation project remains less expensive compared to conventional disposal options, yield as low as 50% of crop optimum could be satisfactory.



Soil/climate	Curve equation	R^2
Arenosol/Hyper-arid (A-HA)	$pH_e = 0.016\ Alk_w + 5.395$	0.8557
Arenosol/Arid (A-A)	$pH_e = 0.0159\ Alk_w + 5.395$	0.8556
Arenosol/Semi-arid (A-SA)	$pH_e = 0.0136\ Alk_w + 5.391$	0.8396
Arenosol/Dry sub-humid (A-DSH)	$pH_e = 0.0095\ Alk_w + 5.390$	0.7926
Gypsisol/Hyper-arid (G-HA)	$pH_e = -0.0002\ Alk_w + 7.592$	0.0002
Gypsisol/Arid (G-A)	$pH_e = -0.0002\ Alk_w + 7.592$	0.0002
Gypsisol/Semi-arid (G-SA)	$pH_e = -0.0002\ Alk_w + 7.594$	0.0002
Gypsisol/Dry sub-humid (G-DSH)	$pH_e = -0.0002\ Alk_w + 7.597$	0.0004

Soil/climate	Curve equation	R^2
Planosol/Hyper-arid (P-HA)	$pH_e = 0.0358\ Alk_w + 5.287$	0.8012
Planosol/Arid (P-A)	$pH_e = 0.0358\ Alk_w + 5.287$	0.8007
Planosol/Semi-arid (P-SA)	$pH_e = 0.0356\ Alk_w + 5.224$	0.8428
Planosol/Dry sub-humid (P-DSH)	$pH_e = 0.0307\ Alk_w + 5.138$	0.8618
Vertisol/Hyper-arid (V-HA)	$pH_e = -0.0013\ Alk_w + 7.261$	0.0013
Vertisol/Arid (V-A)	$pH_e = -0.0013\ Alk_w + 7.261$	0.0013
Vertisol/Semi-arid (V-SA)	$pH_e = -0.0008\ Alk_w + 7.264$	0.0006
Vertisol/Dry sub-humid (V-DSH)	$pH_e = -0.0003\ Alk_w + 7.279$	0.0001

Fig. 5. Soil pH_e and irrigation water alkalinity of the average soil depth 0–60 cm at equilibrium following irrigation with the 15 PWs on Arenosol, Gypsisol, Planosol and Vertisol under hyper-arid, arid, semi-arid and dry sub-humid climates.

4.4. Drainage water

According to the three-way ANOVA the DW quality was significantly related to PW quality and then, climate, while significant differences among soils were only observed on the DW sodicity (Table 4). Increasing EC_w and SAR_w led to higher EC_d and SAR_d (Fig. 2) due to positive correlations between EC_w and EC_d on the one hand, and between SAR_w and SAR_d on the other hand. Although bare differences were observed among soil types (Table 4), soils were, however, determinant in defining DW quality. According to the slopes of the curves $EC_d = f(SAR_w)$ and $SAR_d = f(SAR_w)$ well-drained soils such as Arenosol generated the most saline DW whereas Planosol and Vertisol generated the most sodic DW. Climate interferes as decreasing aridity lowered EC_d and SAR_d by diluting the salinity of DW because of lower evaporation and/or higher precipitation. The crop indirectly determines EC_d and SAR_d through the irrigation volume and irrigation schedule. Also, if the crop requires water in the period of the year when rainfall is the highest and evaporation the lowest, rain could either increase EC_d and SAR_d due to more salt leaching or reduce EC_d and SAR_d due to increasing dilution of DW. Notwithstanding, if the crop requires more water when it rains more, then less PW will be used accordingly, and therefore, less salt will be introduced into the soil.

If irrigation can be sustainable from a soil-plant point of view, DW leaving the root zone must be properly managed to avoid transferring the salinity and sodicity hazards from the soil to the groundwater. Indeed, in the simulations, DW was always more saline and more sodic than the associated irrigation water. DW would continue to percolate deeper into the soil, eventually reaching the aquifer. This risk must be anticipated if EC_d is higher than the EC of the aquifer although it might not be a problem in some dry areas where groundwater is deep and/or already brackish (Vengosh, 2014). Alternatively, DW can be captured by means of drainage systems and reused, treated or disposed of. Disposal options such as pond evaporation, discharge to the sea or deep well injection could be considered (Jiménez et al., 2018). Notwithstanding, irrigation would at least reduce the volume of saline water that had to be disposed of, compared to the original volume of PW,

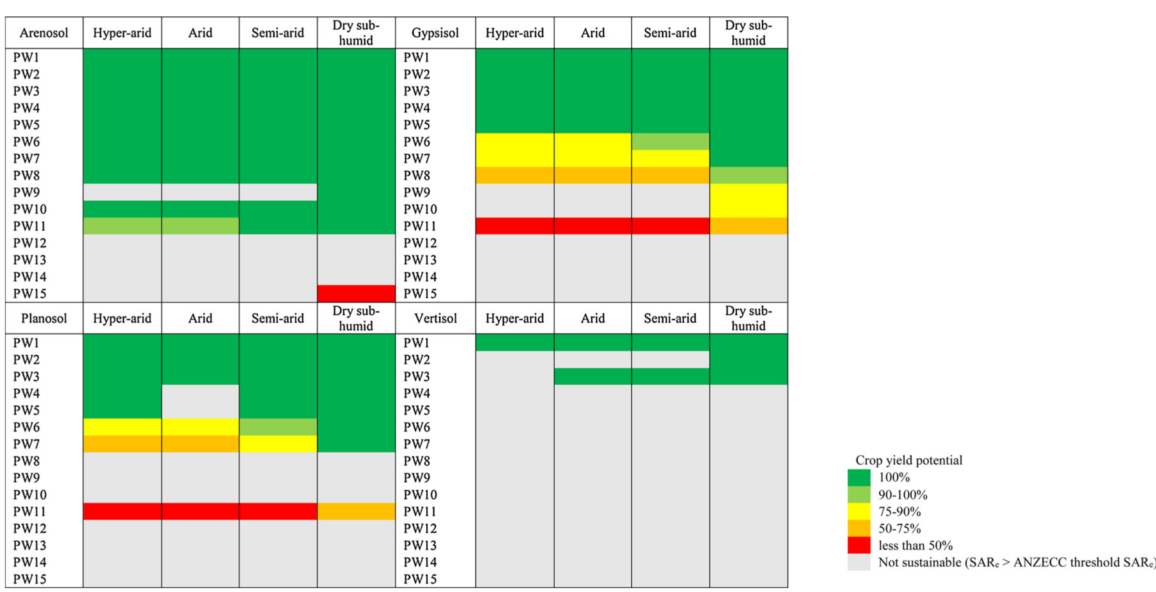


Fig. 6. Estimated crop yield potential of sugar beet irrigated with 15 PWs under hyper-arid, arid, semi-arid, and dry sub-humid climate and on Arenosol, Gypsisol, Planosol, and Vertisol.

therefore it would be cheaper to manage.

4.5. Limitations

The carried out simulations are exploratory and limitations related to the model, the method and the guidelines used in this study are acknowledged.

The SALTIRSOIL_M model does not simulate crop salt uptake, therefore, where this is significant, it could overestimate the soil salinity. Although salt uptake is usually negligible compared to the salt load brought by irrigation water, sugar beet salt uptake can reach more than 1.2 t/ha of sodium and potassium annually (Cumo, 2013). Given that irrigation of sugar beet under dry sub-humid climate requires 590 mm of water (Table 1), irrigation would bring between 0.15 to 118 t/ha/year of sodium and potassium, respectively if PW1 and PW15 are used, that is between 13% and 10,000% of the salt load that would be exported by the crop. Thus, the salt load extracted from the soil solution would not significantly change the salt concentration of the worst case scenarios (e.g. irrigation in a hyper-arid climate with PW15) but would positively contribute to the sustainability of the simulated scenarios where the salt load brought by irrigation water was relatively low.

Tolerance to salinity and optimum soil pH_e vary widely among crops, consequently, different crop threshold levels will also impact soil salinity and sodicity as well as crop yield. The soil salinity and sodicity, and crop yield patterns described in Figs. 1 and 6 would be different if another crop would have been chosen instead of sugar beet.

From an agricultural point of view, the sustainability of irrigation with PW is mainly, but not exclusively a salinity issue. Other constituents of concern, such as metalloids, exist in PW, and their presence and concentrations depend on PW origin (Alley et al., 2011) and treatment processes (Fakhru'l-Razi et al., 2009). On the one hand, the high soil pH_e and the low SOM content of most soils in dryland limit the bioavailability of heavy metals, but on the other hand, high soil EC_e increases this risk (Singh et al., 2009). Although the risks linked to other components of PW are not as concerning as those related to salts, they still deserve to be specifically assessed and included in potential guidelines or frameworks aiming to support PW reuse for irrigation.

Although the SALTIRSOIL_M model has been calibrated and validated against field results in a dry region with slightly to moderately saline irrigation water (Visconti et al., 2014), this has not yet been done for the environments simulated in this investigation. Therefore, the model results should be used in the context of refining conceptual and mathematical models for future research based on a comparison of simulated and field results under specific environments. This would also help to define the sensitivity of sustainability indicators (e.g. EC_e, SAR_e, ions contents, pH_e and alkalinity of the soil solution) to parameters and processes that are considered or not considered in the model and which in this case, would require further characterisation and study.

5. Conclusions

PW is generated continuously, independent of climatic conditions and could be a useful water resource for irrigators in drylands. For petroleum firms, its reuse for irrigation is an alternative to conventional disposal practices which are environmentally risky, increasingly regulated and costly. Depending on the soil and climate, the low quality of PW, particularly its high salinity and sodicity, can degrade soil fertility and aquifers to varying degrees.

Irrigation water quality and climatic aridity drive the balance of salt inputs and outputs of the system, while the irrigation practice and soil type control the salt removal processes and leaching through drainage. The main threat to the soil from irrigation with PW is sodification, the risk of which largely depends on the clay content of the soil, PW sodicity (SAR_w) and aridity. If PW quality cannot be improved (e.g. by blending with freshwater or desalination), PW irrigation can only be used in the long term, in environments that are less vulnerable to soil salinisation and sodification. Well-drained soils with low water content at field capacity (e.g. Arenosol) are less vulnerable to salinisation, whilst a relatively high gypsum content (Gypsisol) provides resistance against sodification. On the contrary, clayey soils with a high field capacity water content and a low gypsum content must be avoided, as the soil structural stability, as well as a tolerable soil electrical conductivity (EC_e) for the crop, cannot be maintained on the long-term.

Simulations with a sugar beet crop in drylands demonstrated that crop yield could be adequate (> 50% of optimum) and even improved by using PW with lower EC in well-drained soils. Soil pH_e, which also impacts crop yield through nutrient availability, was not significantly affected by irrigation water quality since it largely depends on the natural soil $CaCO_3$-CO_2 content.

Finally, drainage water quality is closely linked to the quality of PW but is also influenced by the soil type and aridity. The impact of drainage water on the aquifer must be considered and measures such as drainage-water reuse or disposal implemented accordingly for achieving sustainable irrigation with PW.

The modelling has demonstrated the importance of the clay and gypsum content of the soil and of climate (aridity index) to assess the suitability of produced waters for irrigation. Based on the simulation results, irrigation with PW is likely to be sustainable on sandy soils if PW has an EC ≤ 28 dS/m and a SAR ≤ 36. Loamy and gypsiferous soils can cope with PW with an EC ≤ 14 dS/m and a SAR ≤ 29 unless the climate is dry sub-humid (0.50 ≤ AI < 0.65), in this case, PW with an EC as high as 28 dS/m and a SAR ≤ 83 can be used for long-term irrigation of salt-tolerant crops. Salinisation and sodification can be avoided in sandy clay loam soils if the PW has an EC ≤ 12 dS/m and a SAR ≤ 6. Lastly, clayey soils should not be irrigated with PW with an EC ≥ 2 dS/m and a SAR ≥ 10 except if the climate is dry sub-humid (or wetter) where PW SAR can be as high as 13. These thresholds values need to be confirmed through further field study and would only be adopted to manage PW through irrigation without targeting optimum crop yield. On a sample of 474 PWs collected worldwide, about 6%–8% of PWs fall within the threshold values for the least vulnerable environments (i.e. sandy soil and loamy gypsiferous soil in dry sub-humid climate) whereas only 2% of the PWs corresponded to the required quality for irrigation on clayey soil (Echchelh et al., 2018).

Future work should be carried out to explore how management practices such as over-irrigation, PW blending with freshwater, PW desalination and gypsum amendments could help to improve irrigation sustainability with the PWs that are too saline and/or too sodic to be used in long-term irrigation. A complete sustainability assessment would also require an analysis of the impacts of other constituents of concern such as heavy metals and radioelements on soil, crop and groundwater. These studies could be synthesised in a sustainability assessment framework specifically designed for the oil and gas sector to encourage cooperation between the oil and gas industry and irrigators for sustainable reuse of PW in drylands.

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